Department of AERONAUTICS and ASTRONAUTICS
STANFORD UNIVERSITY

Semi-Annual Progress Report, December 1, 1967 - May 31, 1968

on

EXPERIMENTAL AND ANALYTICAL STUDIES OF PLASMA TRANSPORT PROPERTIES

Submitted to the

National Aeronautics and Space Administration
Washington, D. C.

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ABSTRACT

This report contains a summary of technical progress during the six-month period, December 1, 1967 - May 31, 1968 relating to work supported by the referenced NASA grant. The theoretical effort consisted in extending the work reported earlier on the development of formulas for the calculation of transport coefficients of a stable, multicomponent plasma in the presence of a magnetic and an alternating electric field, in accordance with the Chapman-Enskog theory. It appears that the sixth approximation in the polynomial expansion scheme is well suited for plasmas in an electromagnetic field, but a high approximation is needed to account for electron-atom Ramsauer phenomenon. On the other hand, less exact methods such as the Frost Mixture Rule and the perturbation method have been extended to the calculation of thermal conductivity parallel to the field. Although the latter methods are empirical in nature, the results are found to agree within ten percent with the prediction of the sixth Chapman-Enskog approximation at any degree of ionization. Numerical values of electron thermal and electrical conductivities for helium and argon have been evaluated by the three methods and compared. Major results of the recent experimental effort include a succcessful evaluation of electron density profile in the thermal boundary layer behind the reflected shock. Preliminary comparison with theory shows poor agreement. Further information has also been obtained on the nonequilibrium ionization-wave interactions in the reflection shock regime, and a fuller description of the nature of the phenomenon is now presented. Included in the experimental effort has been further instrumentation work on a more sophisticated thin-film heat transfer gauge for use in ionized gases; as well as continuing work on extending the capabilities of the high response capacitative end-wall pressure gauge.

TABLE OF CONTENTS

LIST OF FIGURES AND TABLES

I. INTRODUCTION

With the present Semi-Annual Report we come to the end of the third year of technical effort support by the present NASA grant. In addition to reporting specific technical progress, the time is appropriate to make a brief overall assessment of the accomplishments in the work so far. Normally, such remarks would be followed by recommendations for follow-on work; however, our previous progress report (ref. 1) already included in some detail a proposal for continuing work which represents our thinking in this connection.

In what follows, we will use the same general format as in previous reports. Thus, the next section will up-date our listing of publications, reports, talks and theses supported by the current grant. The following chapter will present more detail relating to the theoretical studies, and the material will be followed by a description of the recent results of the ionized boundary layer studies and the ionization-wave interaction studies. The last two sections will deal respectively, with the heat transfer gauge and pressure gauge development work. The brief assessment referred to above, will then conclude the report. For the record, we should add that our present policy in technical writing is to concentrate on publications in the archive journals and make less use of the laboratory reports. Details of a particular program can almost always be found in the thesis of the student working on the program. De-emphasis of reports published in our own laboratory provides better cost control and makes for less duplication. In Section II those publications which have been added since the last Progress Report are Items 4(b), 4(c), 9(b), 11 and 16. Newly completed Ph. D. programs number two, with a third related Ph. D. program (pressure gauge studies) completed largely under other auspices.

II. LISTING OF PUBLICATIONS, REPORTS, TALKS AND PH.D. THESES SUPPORTED BY PRESENT GRANT

1. R.S. Devoto, "Approximation for the Properties of a Two-Temperature Ionized Gas," APS Bulletin 11, 554 (1966).

2. R.S. Devoto, "Comments on the Transport Properties of Hydrogen," AIAA Journal 4, 1149 (1966).

3. (a) K.P. Horn, "Radiative Behavior of Shock-Heated Argon Plasma Flows," Stanford University, Department of Aeronautics and Astronautics SUDAAR No. 268, May 1966 (partial support); also Ph.D. Dissertation.

   (b) K.P. Horn, H. Wong and D. Bershader, "Radiative Behavior of a Shock-Heated Argon Plasma Flow," J. Plasma Physics 1, 157, May 1967.

4. (a) S.P. Knöös, "Analysis of Boundary Layer Structure in a Shock-Generated Plasma Flow, Part I. Equilibrium Ionization," Stanford University, Department of Aeronautics and Astronautics, SUDAAR No. 277, May 1966, (partial support).

   (b) S.P. Knöös, "Boundary-Layer Structure in a Shock-Generated Plasma Flow. Part 1. Analysis for Equilibrium Ionization," J. Plasma Physics 2, 207, June 1968.

   (c) S.P. Knöös, "Boundary-Layer Structure in a Shock-Generated Plasma Flow. Part 2. Experiments Using a New Quantitative Schlieren Technique," J. Plasma Physics 2, 243, June 1968.

5. (a) P.E. Oettinger, "A Unified Treatment of the Relaxation Phenomena In Radiating Argon Plasma Flows Behind Incident and Bow Shock Waves," Stanford University, Department of Aeronautics and Astronautics,

SUDAAR No. 285, July 1966 (partial support); also Ph. D. Dissertation.

(b) P. E. Oettinger and D. Bershader, "A Unified Treatment of the Relaxation Phenomenon in Radiating Argon Plasma Flows," AIAA Journal 5, 1625, September 1967.

6. (a) R. S. Devoto, "Simplified Expressions for the Transport Properties of Ionized Monatomic Gases," Stanford University, Department of Aeronautics and Astronautics, SUDAAR No. 283, July 1966.

(b) R. S. Devoto, "Simplified Expressions for the Transport Properties of Ionized Monatomic Gases," Physics of Fluids, 10, 2105, October 1967.

7. (a) R. S. Devoto and C. P. Li, "Transport Coefficients of Partially Ionized Helium," Stanford University, Department of Aeronautics and Astronautics, SUDAAR No. 291, December 1966.

(b) R. S. Devoto and C. P. Li, "Transport Coefficients of Partially Ionized Helium," J. Plasma Physics, Vol. 2 - Pt. 1, January 1968.

8. R. S. Devoto, "Transport Coefficients of Partially Ionized Argon," Physics of Fluids 10, 354 (1967).

9. (a) J. O. Bunting and R. S. Devoto, "Deduction of the Thermal Conductivity of Atomic Argon from Interferometric Measurements of the End-Wall Thermal Layer in a Shock Tube," Stanford University, Department of Aeronautics and Astronautics, SUDAAR No. 313, July 1967.

(b) D. Bershader, J. O. Bunting and R. S. Devoto, "Thermal Conductivity of Shock-Heated Argon," Bulletin of the American Physical Society, Vol. 13, 786, May 1968.

10. R.S. Devoto, "Third Approximation to the Viscosity of Multicomponent Mixtures," Physics of Fluids 10, 2704, December 1967.

11. R.S. Devoto and C.P. Li, "Fifth and Sixth Approximations to the Electron Transport Coefficients," Physics of Fluids, 11, 448, February 1968.

12. R.S. Devoto and C.P. Li, "A New Method for Computing the Electrical Conductivity of Weakly Ionized Gases," presented at the 8th International Conference on Ionization Phenomena in Gases, Vienna, Austria, August 27 - September 2, 1967.

13. R.S. Devoto, "Convergence of the Approximation to the Electrical Conductivity of Helium and Xenon," presented at the 8th International Conference on Ionization Phenomena in Gases, Vienna, Austria, August 27 - September 2, 1967.

14. R.S. Devoto, "Theoretical Prediction of Transport Coefficients in Partially Ionized Gases," paper presented at GAMM Specialists Conference on Electro- and Magnetohydrodynamics, Technische Hochschule, Aachen, Germany, October 1967.

15. P.E. Oettinger, "Measurements of Argon Shock Layer Electron Densities," AIAA Journal 6, 150, January 1968.

The following students have been awarded Ph. D. degrees on the basis of research supported by the present NASA grant:

Peter Oettinger

Kenneth Horn

Stellan Knöös

Jackie Bunting

C. P. Li

Ralph Kuiper (end of summer, 1968)

In addition, four students are currently engaged in Ph. D. dissertation research studies in connection with the present program.

III THEORETICAL STUDIES OF TRANSPORT PROPERTIES*

During the past six months we have made further studies on the applicability of the Chapman-Enskog expansion method to laboratory plasmas in the presence of a magnetic field. The numerical computation has been performed for the tensor electrical conductivity and thermal conductivity contributed by electrons of a Lorentzian gas, in which the interaction among electrons themselves is neglected. Thus, the closed form solution for the Lorentzian gas is used to compare with the solutions resulting from various approximations in the Chapman-Enskog scheme.

In Fig. 1 we have plotted the ratios of solutions of the third and sixth approximations to those obtained by the Lorentzian formula. The Hall component of electrical conductivity of a Lorentzian helium plasma is expressed as a function of temperature over a whole range of ionization and as a function of strength of magnetic field. The deviation of the third approximation to the true solution σ_L is about ten percent at 1000 gauss. The accuracy of this method improves when the sixth order approximation is used in the computation, as shown in the bottom part of Fig. 1. We see that those curves are close to unity, while only five percent error can be estimated at most. This is a quite satisfactory result from the point of view of practical calculation. The transverse component shows a similar trend as the function of temperature and magnetic field; we will not discuss it in this report.

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* This material is presented in greater detail in the Ph.D. thesis of C. P. Li, reference 2.

Next, we have applied the expansion method to the case of electron thermal conductivity of a Lorentzian argon plasma in an effort to study the effect of the electron-atom interactions on the convergence of the approximated solution. After expressing the ratios $\lambda_K^H / \lambda_L^H$ versus temperature for magnetic field strength of 1000 and 20000 gauss, we note that these curves display a rapid variation near temperature 7000 $^{\circ}$K. This phenomenon may be attributed to the anomalous cross-section variation associated with the electron-argon atom Ramsauer effect, although that phenomenon is strangest at a somewhat lower temperature, around 0.4 eV. Fortunately, this behavior is much improved as the the order of approximation increases, the deviation decreasing to less than ten percent at 1000 gauss when the sixth approximation is performed. Note that the particle interactions have less influence on the convergence of the expansion method for larger values of magnetic field.

The rate of convergence of successive approximations up to sixth approximation is examined in Table 1 for a Lorentzian helium plasma. Ratios of the approximate solution to the true one exhibit an oscillatory variation but converge to the value of unity as the order of approximation goes higher. The rate of convergence is rather rapid except for the smallest values of Hall parameter, $\omega\tau$. But even in that case a fourth approximation already provides an accurate solution. Therefore, we see that the Hall parameter is not an important factor in regard to the convergence of the expansion method. We may also conclude that the sixth approximation is well suited for general use in the prediction of transport tensor coefficients; but a still higher approximation is evidently necessary to take account of rapid variation in the elastic collision cross-sections of species in the plasma.

Finally, we have also shown that the effects of both magnetic field and alternating electric field can be treated at the same time on the basis of the Boltzmann equation. This part of the analysis relates to studies of microwave transmission through an ionized medium, an area of considerable current interest. With a certain amount of manipulation, the procedure established for the calculation of tensor coefficients can be modified to include the effect of an alternating electric field. If a complex formulation is used, we are able to represent the transport coefficients as three by three matrices composed of three independent complex components. The results obtained for plasmas in the presence of a magnetic field and a static electric field can be interpreted for the case of plasmas in the presence of an alternating electric field. For instance, the reciprocal of the complex quantity $1/(\sigma^T + i\sigma^H)$ would constitute essentially a complex impedance.

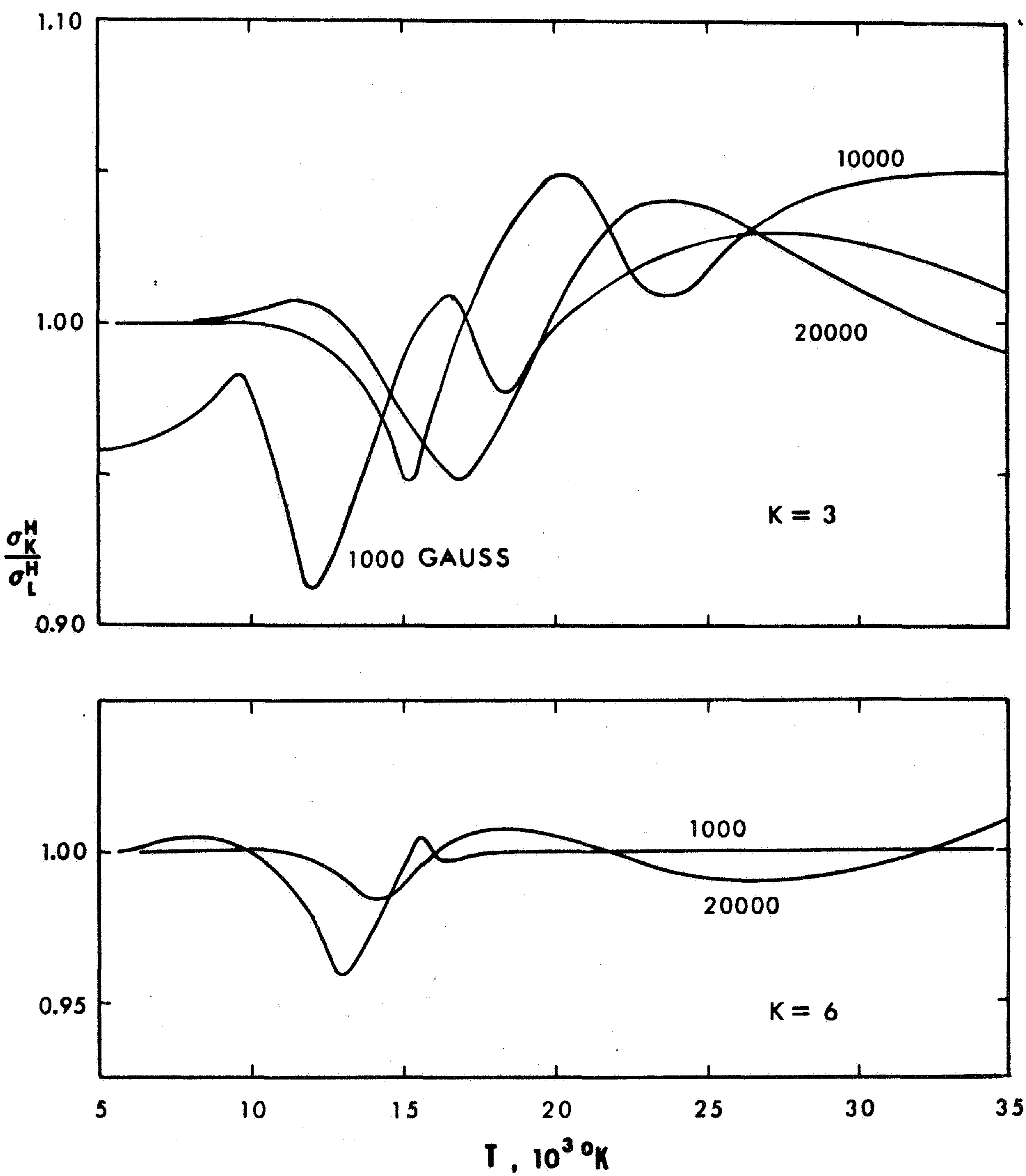


Fig. 1: Convergence of the third and sixth approximations in the Chapman-Enskog expansion method to the Hall electrical conductivity of a Lorentzian helium gas at 1 atm pressure, σ_L is the Lorentzian value of electron thermal conductivity.

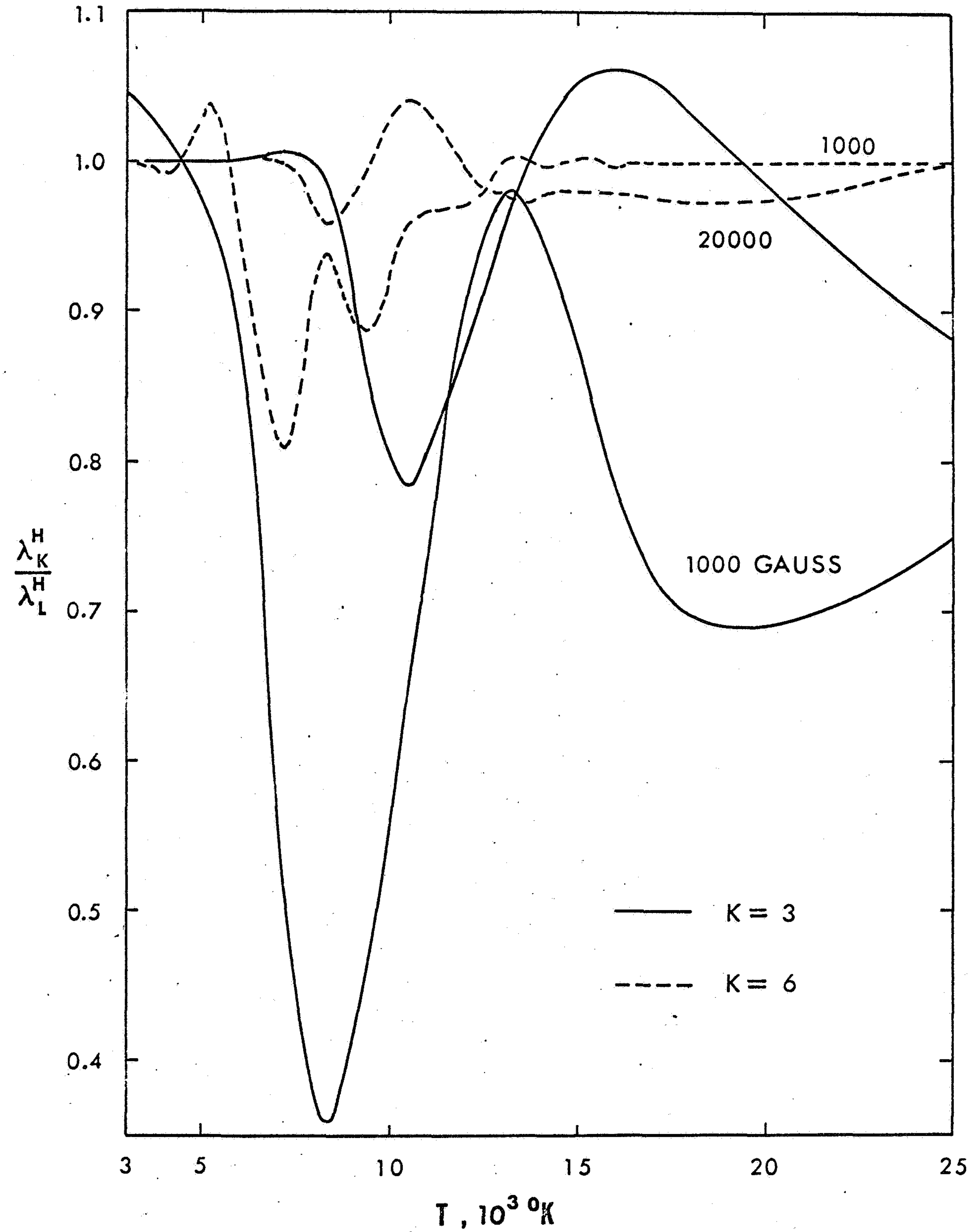


Fig. 2: Convergence of the third and sixth C.-E. approximations in the expansion method to the Hall electron thermal conductivity of a Lorentzian argon gas at 1 atm. σ_L is the Lorentzian value of electrical conductivity.

T	$\omega\tau$	r/λ_d	σ_1/σ_L	σ_2/σ_L	σ_3/σ_L	σ_4/σ_L	σ_5/σ_L	σ_6/σ_L
5000	2.35	0.001	1.0605	1.0080	1.0013	1.0013	1.0011	1.0010
10000	2.97	1.496	1.0317	1.0074	1.0042	1.0043	1.0042	1.0041
15000	0.718	16.91	1.0963	0.9436	0.9510	0.9782	0.9959	0.9963
20000	0.159	52.10	0.5832	0.9632	1.0187	0.9960	0.9945	0.9988
25000	0.116	72.73	0.4953	1.0363	1.0081	0.9872	0.9975	1.0021
30000	0.153	70.63	0.5819	0.9788	1.0313	0.9887	0.9912	1.0001
35000	0.206	65.86	0.7190	0.9007	1.0448	1.0060	0.9884	0.9936

Table 1. Convergence of successive approximations to the transverse electrical conductivity of a Lorentzian-helium gas at 1 atm and 5000 gauss.

IV. WAVE INTERACTION AND ELECTRON DENSITY MEASUREMENTS NEAR THE END WALL

A significant development during this report period was the successful experimental resolution of electron concentration and mass density distribution in the ionized-argon, end-wall boundary layer. Previous difficulties were traced to a schlieren-type interaction between the refracted light and the edges of the radiation stop placed at the focal point of the field lens. Some additional information has also been obtained concerning the shock reflection process in ionizing argon, and the data reduction has been completed for both the streak interferograms of the shock reflection process and the snapshot interferograms of the boundary layer study. Since the experimental techniques employed were discussed in the last progress report, only the results will be considered here. The present comments on the reflected wave interactions represent a preliminary analysis, as does this first discussion on the electron density profiles. Regarding the latter study, we will compare one set of data with the theoretical analysis of S. Knöös[3].

Figure 3 is a schematic scale drawing of one of the streak interferograms showing on x - t diagram of the shock reflection process in ionizing argon. The wave interactions shown result when the incident shock strength is great enough to cause ionization behind the reflected and incident shock waves. Since the density ratio (ρ_{5E}/ρ_{5F}) across the reflected ionization front, I_5, is approximately 1.7, an expansion wave system must originate at the point of equilibration on the wall in order to supply the necessary mass addition for the density increase. Because the front of this expansion wave travels at the sonic speed in region 5F, it will overtake the translational shock which is traveling subsonically relative to the fluid in region 5F, and cause it to decelerate.

For the case considered here, the density increases by a factor of 1.5 across the incident shock ionization front, and since this increase takes place in only the last 20 percent of the time τ_{2L}, its resulting interaction with the reflected shock wave may be considered similar to that of the "head-on collision" of two normal shock waves. The reflected shock is transmitted through I_2 and I_2 is transmitted as a compression wave called the "interaction wave," as shown in the diagram. This interaction wave subsequently reflects from the wall and coalesces with the transmitted reflected shock. The observed contact surfaces shown in the diagram result from the fact that although the fluid velocity, represented by the particle paths, and pressure are the same on either side of the contact surface, the fluid has been precessed by shock waves of varying entropy production. Hence, the other thermodynamic properties differ across the contact surface.

Another phenomenon observed on the streak interferograms is the boundary layer bifurcation shock. The latter, which is not ordinarily present at low Mach numbers in argon, is "triggered" by the onset of ionization behind the incident shock. The so called bifurcation results from the inability of the fluid in the incident side wall boundary layer to negotiate the adverse pressure jump presented by the reflected shock wave. Boundary layer separation then occurs along with the formation of an oblique shock system on the "foot" of the normal reflected shock wave. This phenomena practically always occurs in polyatomic gases except for very low Mach numbers, i.e., $M \leq 1.5 - 2.0$.

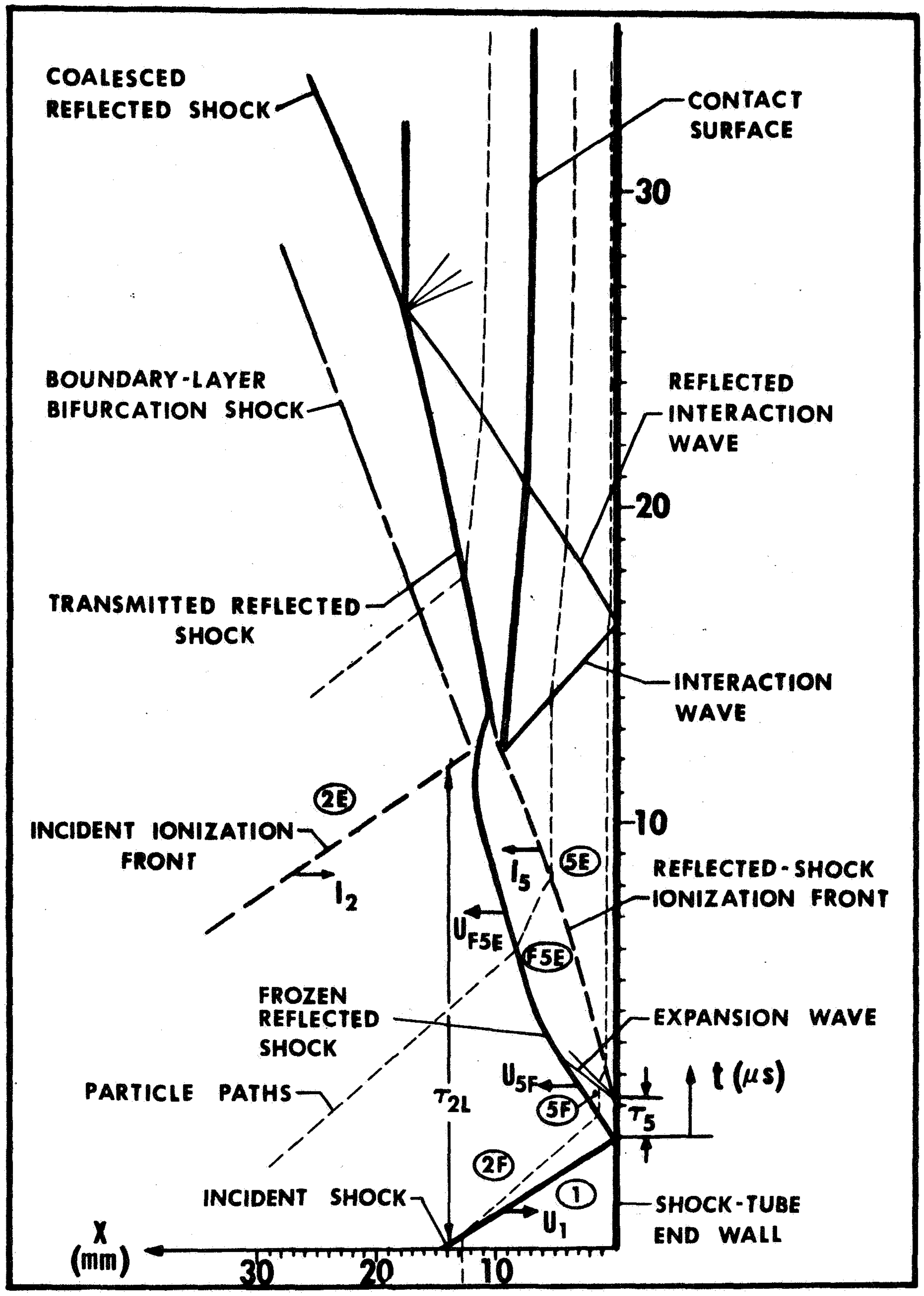
The quantitative results from the shock reflection studies provided the freestream properties that were used in the interferometric studies of the ionized, end-wall, boundary layer. The measurements reported here were made in a manner similar to that used for the un-ionized boundary layer as discussed in the last progress report. The experimental results for one run are shown in figure 4 where they are compared with the results obtained from the theory of reference 3. The primary discrepancy, which occurs in the electron concentration or degree of ionization, cannot be accounted for by consideration of experimental errors or uncertainties. Although at present no detailed corrections have been made to the theoretical calculations, it appears that a consideration of four of the basic assumptions of the theory would yeild the most fruitful results. In particular, the assumptions of primary interest are

1. chemical equilibrium in the boundary layer,
2. no radiation coupling between the boundary layer and freestream
3. no net electrical current into the wall,
4. the transport properties used in the calculations.

It is readily apparent that deviations from the first two of these assumptions would act in such a way as to cause the presently observed discrepancy. An indication that the assumption of chemical and thermodynamic equilibrium is questionable arises when the temperature distribution and subsequently, the pressure distribution in the boundary layer are computed based on this assumption and the measured properties. It is then found that the pressure computed in this way is not constant, but increases toward the wall. It is not likely that the induced velocities in the boundary layer are large enough to cause this measurable variation in pressure; hence, one may conclude that the requirements for equilibrium are not satisfied.

Radiation from the freestream may provide energy to the boundary layer fluid sufficient to maintain a higher degree of ionization closer to the wall than would be otherwise predicted.

The immediate consequences of deviations from the third assumption and those incorporated in the evaluation of the transport properties are not so readily seen. The assumption of no net current at the wall may in fact be quite dubious, and the role of the plasma sheath at the wall is not fully clear. The evaluation of the transport properties requires a knowledge of several appropriate cross-sections, and even if one could state apriori the direction of possible errors in transport properties, the resulting effect on the boundary layer profile is not nearly as abvious as for the un-ionized case. A more quantitative analysis of these remarks is presently being made and will be included in the Ph. D. thesis of Ralph Kuiper and in a subsequent publication.



SHOCK REFLECTION PROCESS IN IONIZING ARGON $M = 12.7, P_1 = 5$ TORR

Figure 3: Distance vs. time (x-t) diagram of shock reflection process in ionizing argon.

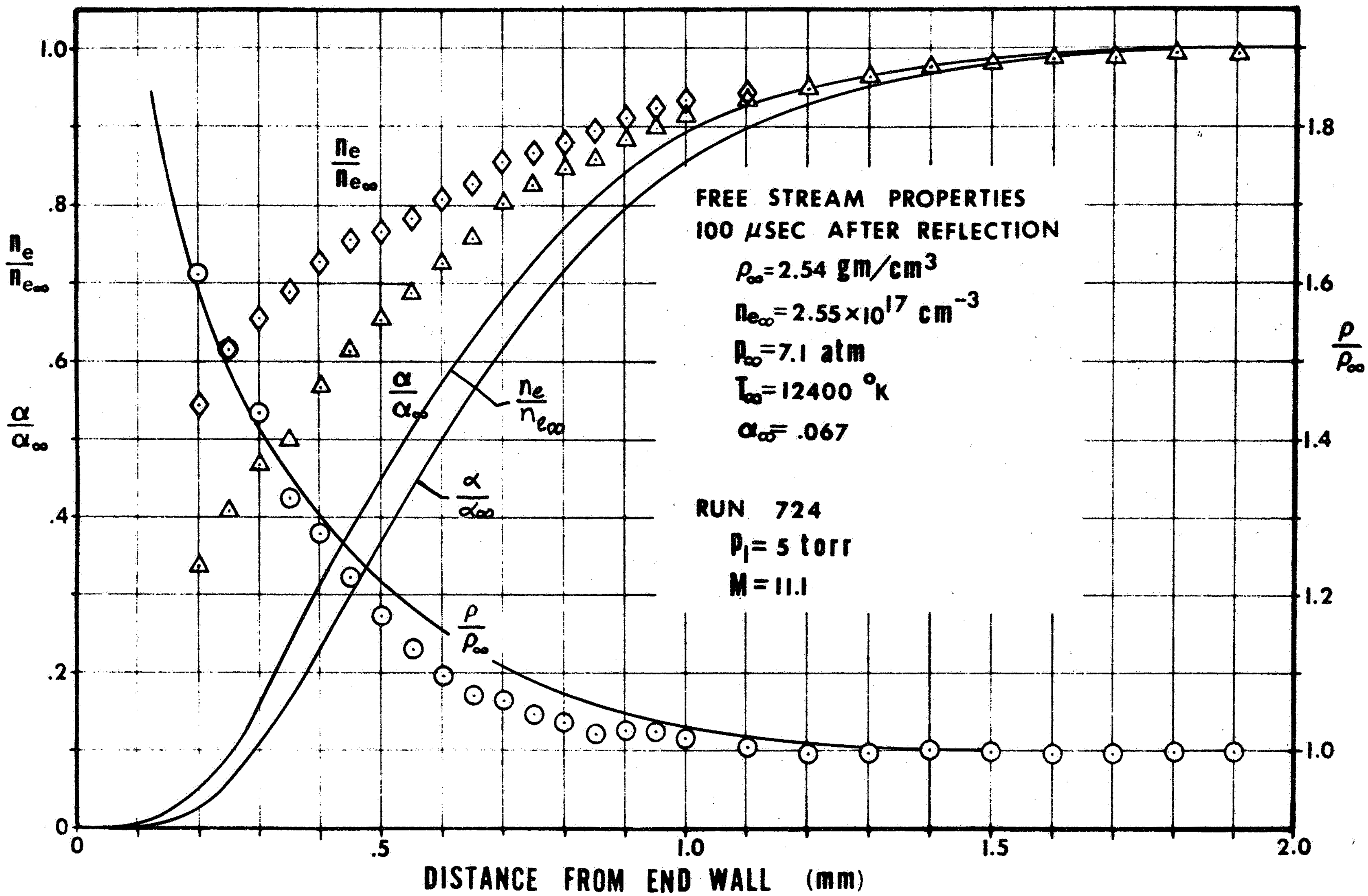


Figure 4: Comparison of experimental, ionized, end-wall boundary layer with theory (Knoos, ref. 3).

V. INSTRUMENTATION DEVELOPMENT

1. Shock Tube End-Wall Heat Transfer Studies

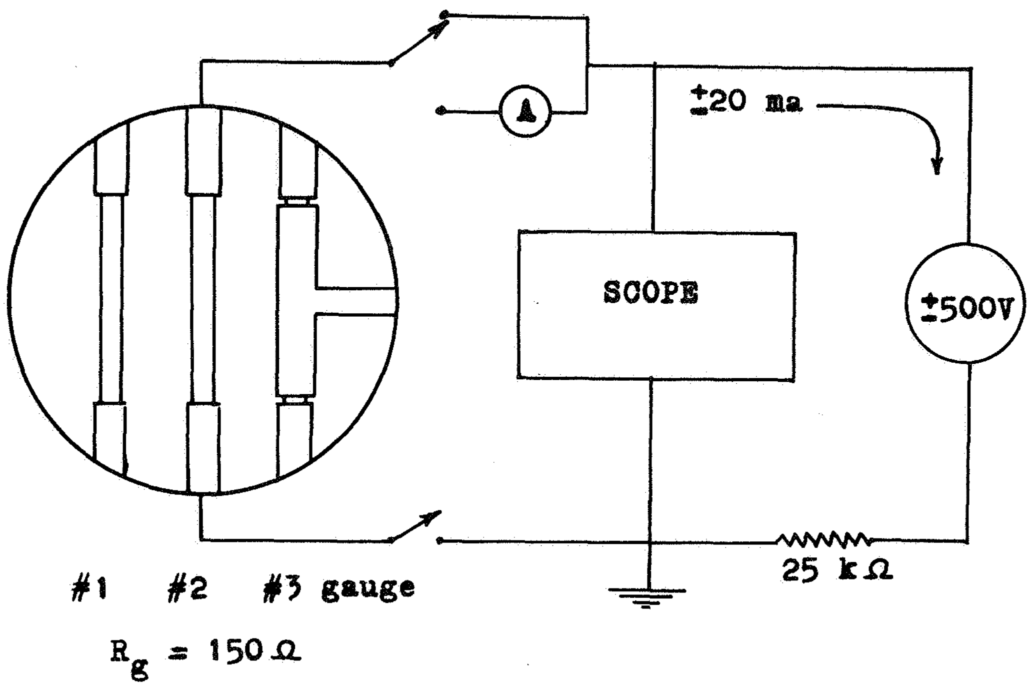
A thin film gauge has been developed which measures heat transfer rates at the end wall of a shock tube under temperature conditions higher than possible with standard thin film gauges. In previous progress reports we have indicated the desirability of determining thermal conductivity of a gas from heat transfer measurements, and have given some preliminary results obtained with the use of a gauge still under development.

The stage in the design development of our latest device is shown in Figure 5. Three thin film heat transfer gauges are deposited onto a quartz disc which is then embedded into the shock tube end-wall. All three gauges are evaporated onto the quartz substrate under vacuum conditions. The first gauge is a simple thin film for use in the non-ionized gas regime. Heat transfer into the constant current film changes its resistance which is monitored as a voltage change. The second gauge is for use with ionized gases and is like the first, but coated with an extra dielectric layer which protects the sensing film from being shorted out by the electrons in the plasma. The third gauge has an additional conducting film evaporated over the dielectric insulator so that the dielectric strength of the dielectric insulator may be determined.

Constructing such a device has been found to be extremely difficult. Microscopic examination of film surfaces has revealed some problems which are not usually observable with the naked eye. Three such problems are indicated in Figure 6. Pertinent problems include the cleanliness, the coefficient of thermal expansion, and the crystalline structure of the substrate. Adhesion and uniformity of the metallic film are largely a function of the type of metal, the substrate temperature during evaporation, and the evaporation rate. However, the largest difficulty was found to be the presence of microscopic pinholes in the dielectric. Nonetheless, we have developed a technique of depositing a good dielectric film. A gauge using such films was tested on the shock tube end-wall and did not deteriorate during 60 runs in argon at Mach numbers less than 10. Most experiments were done under conditions giving argon temperatures of about 10,000°K upon shock reflection from the end-wall. Conventional thin film measurements have previously been limited to temperatures up to 5,000°K in argon[4, 5].

The signals received by an uncoated and a dielectrically insulated gauge are compared in Figure 7. While the uncoated gauge signal is spurious for all times after shock reflection at the end-wall, the coated gauge signal shows noise only during shock reflection. The indicated signal of the coated gauge after the initial spiking has been shown experimentally to be entirely due to heat transfer.

Our test results with the above gauge have indicated that some design improvements can still be made. A device incorporating these improvements can still be made. A device incorporating these improvements is presently being fabricated and will be used for actual shock tube experimentation. In particular, we look forward to the use of the gauge in the study of thermal transport in molecular gases at high temperatures, in accordance with a future phase of this program.

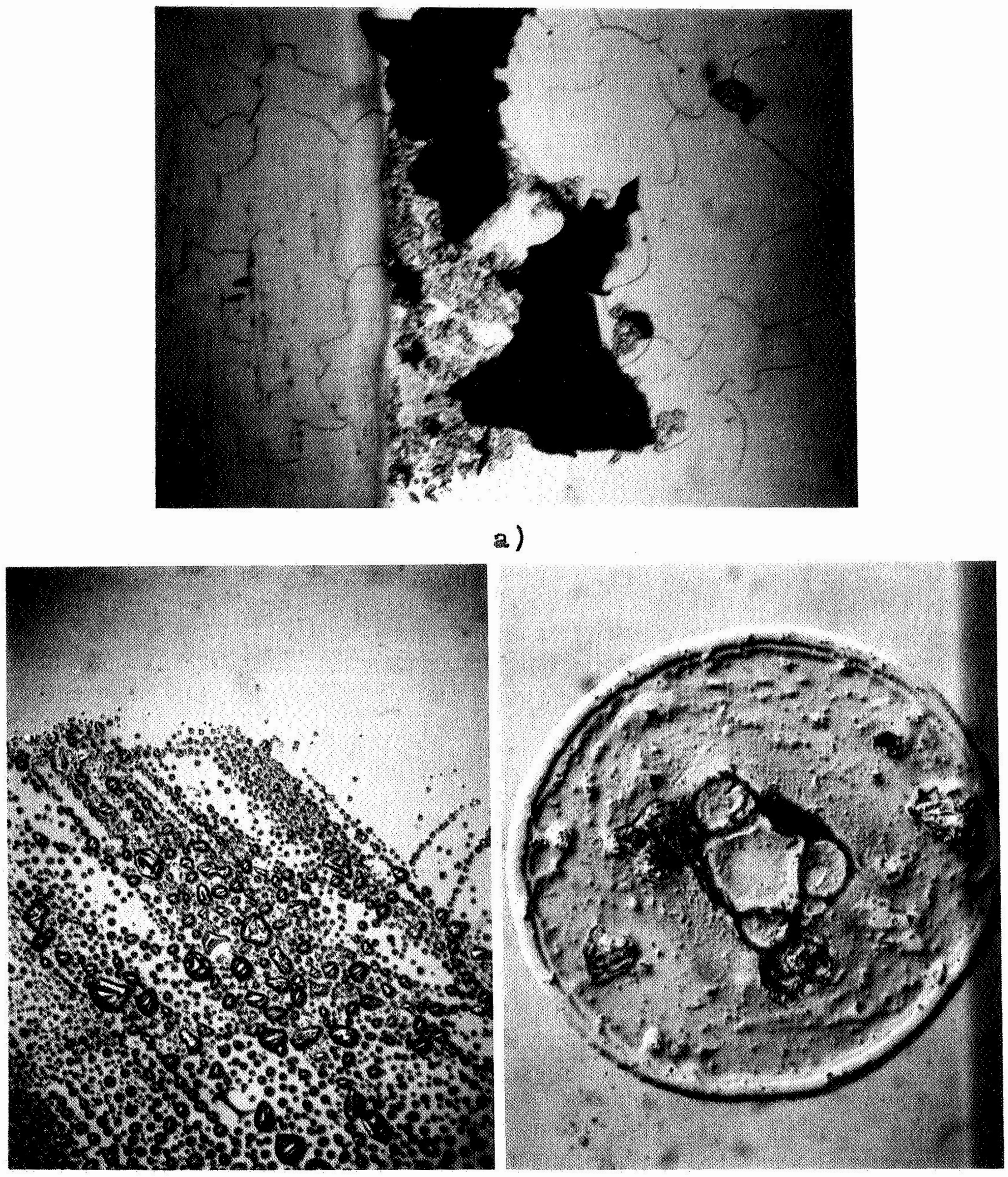


Composition of gauges:

Substrate: fire polished fused quartz
Leads : silver painted and baked onto quartz, coated by 13,000 Å of SiO
Films :

	#1	#2	#3 gauge
50 Å of Cr - bond	#1	#2	#3 gauge
500 Å of Pt - conductor	#1	#2	#3 gauge
50 Å of Cr - bond		#2	#3 gauge
3,000 Å of SiO- dielectric		#2	#3 gauge
50 Å of Cr - bond			#3 gauge
500 Å of Pt - conductor			#3 gauge

Figure 5: Heat transfer measurement device.



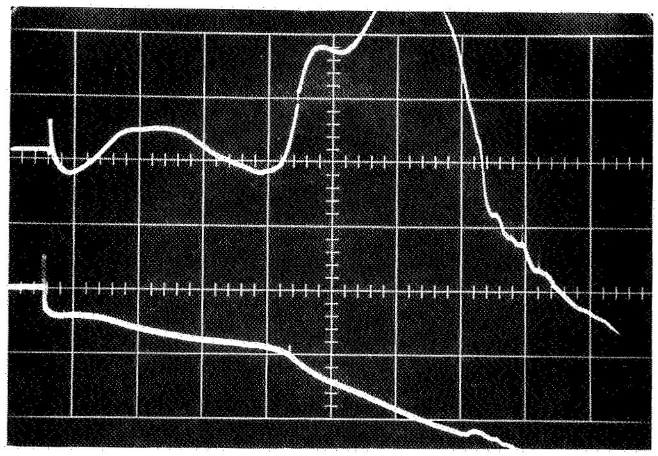
a)

b) .01 inch c)

Figure 6: Microscopic photos of evaporated film problems
a) Film cracking due to thermal expansion mismatch
b) Film peeling due to surface impurities
c) "Crater" due to sputtered particle from evaporation source.

uncoated gauge

coated gauge

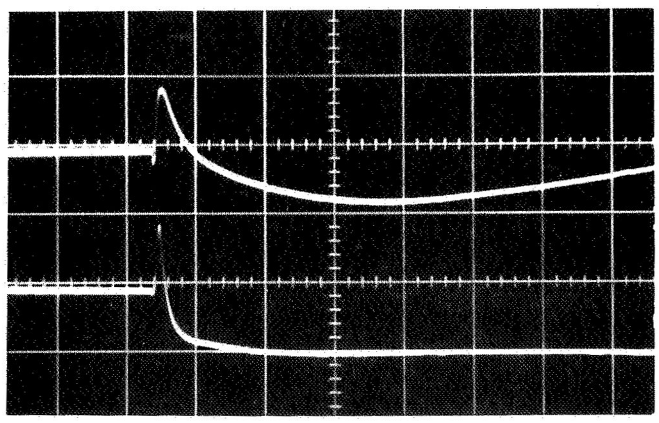


contact surface
perturbs plasma

200 mv/div, 100 μ sec/div

uncoated gauge

coated gauge



100 mv/div, 10 μsec/div

M=7 into 5 mm Hg of Argon
T_5= 9,600°K

Figure 7: Comparison of signals from coated and uncoated gauges.

2. Pressure-Gauge Instrumentation Studies

The pressure in the reflected region of a shock tube is, in general, a very difficult quantity to predict theoretically when real gas effects are present. The flow is basically nonsteady and cannot be reduced to a steady flow by a coordinate transformation. Knowledge of the detailed pressure variation in the reflected region is important however because the pressure varies markedly for the different relaxation processes. This is in contrast to the situation behind the incident shock wave where it is well known that the pressure variation is very small for most conditions.

The end-wall pressure history is a smooth monotonic function for some processes and is quite complicated for others. For example, vibrational relaxation and dissociation yield relatively simple pressure histories over their respective characteristic time scales; examples are given in figures 8 and 9. For very strong shock waves in CO_2, the end-wall pressure history is not so easy to interpret since the real gas effects become very complicated. This is exhibited in figure 10 for the test conditions $p_1 = 4$ Torr and $M_s = 18$. It can be shown from an analysis of this test condition that all relaxation processes (vibration and dissociation) should be completed within a short portion of the displayed test time, yet major wave-like motions continue to persist. Thus, two points suggest themselves: the character of the flow in the reflected region of the shock tube should be checked with the pressure gauge for each test condition, regardless of whether or not pressure data are of primary interest in an experiment; and the pressure variations are not only large in amplitude but, at times, they have a time-variation that can only be determined experimentally.

The time scales for vibrational relaxation, dissociation and ionization can almost always be adjusted, by altering the initial pressure, to match the useful recording time of the pressure gauge (10μ/sec in a 2-inch-diameter shock tube) when the study of these processes is the primary motive in an experiment. However, when the initial pressure is determined by other considerations, the useful time of the gauge may not be long enough. Therefore, it is of interest to try to extend the time interval over which the pressure gauge will yield data in a given shock tube.

One method for increasing this time interval is to use a material for the gauge element which has a very low speed of sound. The most promising material at this time appears to be Teflon which would replace Lexan, the material presently being used. If this exchange proves to be practical, one could expect a factor of approximately 4 between the useful times for the two gauges, i.e. the pressure gauge could be used to record signals up to 40μsec in duration. The reason that Teflon has not been used in the past is due to the fact that it has always been an extremely difficult plastic to bond, and only recently have promising bonding agents become available. New construction techniques are presently being investigated, and it is hoped that tests with a Teflon gauge will be completed soon.

As part of the effort to construct a pressure gauge from Teflon, new approaches are being considered for the construction of the capacitive elements needed in the gauge; in previous gauges these were constructed with conducting-epoxy electrodes. We are presently considering the use of very thin ($\approx$0.0002 inches thick) electroformed screens made of nickel. As discussed in the previous progress report, very thin nickel foil has been tried and reasonably good results were obtained. However, the gauge response with the foil electrodes exhibits several small oscillations near the front of a square-wave pressure signal, and this effectively increased the rise time of the gauge to about 0.5μsec (see figure 11). A screen electrode should be superior to a foil electrode on two accounts. Firstly, a metal screen buried in a plastic medium should present less of an impedance mismatch to an incident stress wave than a continuous metal foil; and secondly, a superior bonded joint can be obtained when a screen is placed between the two plastic halves than when a foil is placed in the same position. The disadvantage of screen electrodes over foil electrodes is, of course, that the effective area of the capacitor is reduced somewhat. An unexpected advantage of using the electroformed screen has been that the screen is surprisingly much easier to handle than the foil, for the same thickness.

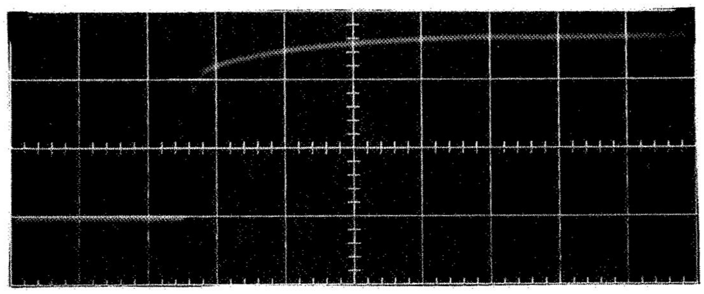


Figure 8: Vibrational relaxation in N_2; $p_1 = 10$ Torr, $M_s = 8.2$, sweep = 1μsec/div.

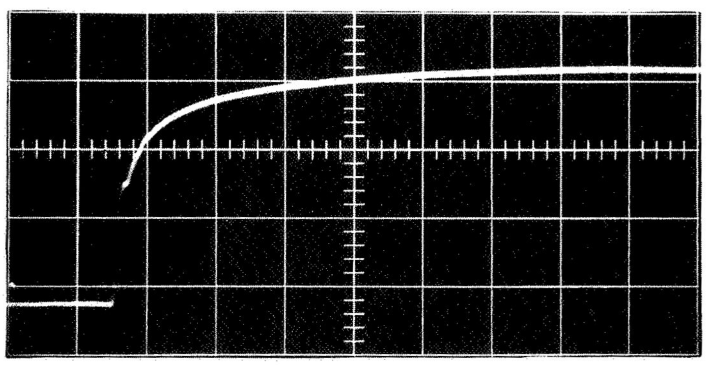


Figure 9: Dissociation in N_2; $p_1 = .86$ Torr, $M_s = 17$, sweep = 1μsec/div.

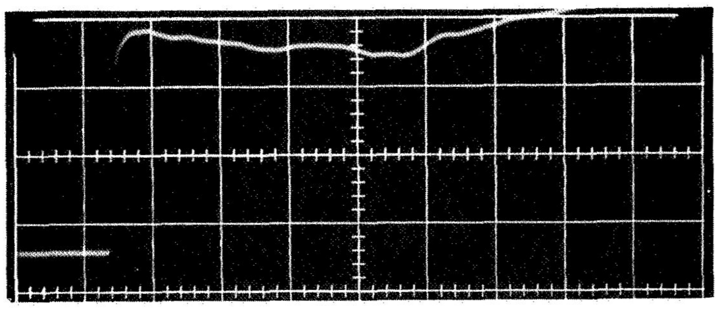


Figure 10: Pressure waves induced by real gas effects in CO_2; $p_1 = 4$ Torr, $M_s = 18$, sweep = 2μsec/div.

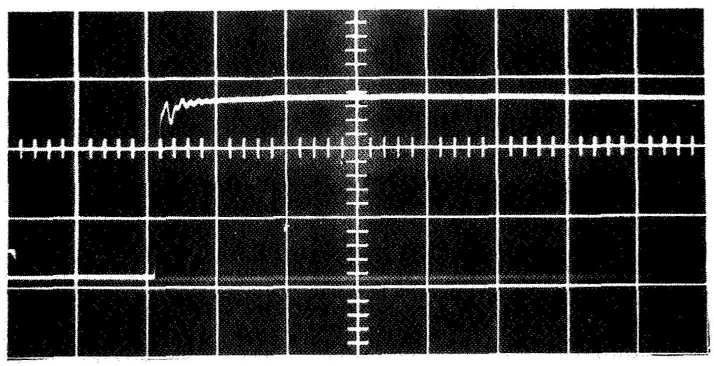


Figure 11: Gauge response with thin nickel-foil electrodes; sweep = 1μsec/div.

VI. BRIEF ASSESSMENT OF ACCOMPLISHMENTS TO DATE

The current program has evolved from the premise that significant contributions to understanding of the properties and behavior of partially ionized gases in the high density, moderate temperature range could result from a highly quantitative study of shock heated gases together with the corresponding theoretical analysis. The problem areas chosen for study, as indicated in our several progress reports and archive publications, have been generally in line with the objectives as stated in the original proposal. A further desirable by-product, characteristic of the university scene, has been the advanced training of several graduate students at the Ph. D. level. As expected, the latter are now making use of their training in various educational and research institutions throughout the country.

The technical area itself is a difficult one for at least two reasons. Firstly, values of several important physical parameters, e.g. cross sections, are not well known. Secondly, although the intrinsic physical basis of the phenomena under study is regarded as understood, the particular model chosen for the analysis of a selected problem must of course be regarded as an assumption of the analysis. The complexity of problems dealing with partially ionized gases which are radiating and which are generally not in thermal or chemical equilibrium are such that a demonstration of consistency between the assumed model and the theoretical and experimental results itself must be regarded as a step forward.

The above approach has in fact been followed in much of the work today such as, for example, the work on radiative cooling of a shock heated argon plasma, the studies of high temperature end-wall boundary layers, and the studies of kinetic processes induced by a shock wave as a guide to the transport behavior of the gas.

There were, of course, extensions of both the theoretical and experimental work, respectively, beyond the point where cross comparisons could be made. Significant progress was made in our understanding of the importance of the higher approximations in the expansion formalism for solution of the Boltzmann equation as applied to noble gases under the conditions of interest in the present work. Thus, we have seen more clearly than before the importance of thermal diffusion in the heat conductivity at higher temperatures, the significant change in viscosity brought on by the charge exchange cross section in partially ionized argon, and the influence of the Ramsauer reduction of elastic cross section in resisting attempts to compute smooth temperature variations for transport coefficients in the fractional electron-volt range. The most recent studies have been extended to include the presence of a magnetic field as a further parameter.

On the experimental side, we feel that for the present series of investigations, the choice of a diaphragm-driven shock tube of optimal design to produce partially ionized plasma for our studies has in fact been a wise one. The degree of definition, uniformity and consistent behavior over periods of time exceeding 100 microseconds has given confidence that we have a well-defined base on which to perform studies planned for the program. In the temperature and density range of interest, our particular shock tube and interferometer combination provided measurements of electron density which were probably more accurate than could be obtained by any other device. The definition of electron density and other conditions defining the state of the gas was superior to that obtainable in plasma jets, pinches, discharges or other known accelerator devices. For the period of time involved, the quantitative capabilities are comparable with those of a highly stabilized arc.

As expected, an appreciable part of the effort involved the analysis and development of particular experimental methods and techniques. An extended discussion could be given to illustrate the several difficulties encountered. Many of these were overcome, such as for example, the schlieren darkening due to the radiation stop acting as a knife edge, and interfering with our measurements of electron density profiles in the boundary layer. Clearly, problems of experimental methodology will constitute an important part of foreseeable studies in all phases of high temperature gas dynamics and plasma dynamics. Improvements in facilities and measurements are the means to progress in this area. In this connection the modest size of our equipment has provided the flexibility for change and modification.

Supplementing the use of interferometry with spectroscopic studies of resonant transfer behavior and with laser absorption techniques for molecular kinetics studies should provide us with a most versatile set of quantitative optical methods in the future. Application to molecular problems, and possibly to the study of the state of ultra-dense plasmas at somewhat higher temperatures appear to be feasible and are being explored along the lines of our follow-on proposal in reference 1.

REFERENCES

1. Semi-Annual Progress Report, December 1, 1967 to May 31, 1968, NASA Grant NGR-05-020-091, Department of Aeronautics and Astronautics, Stanford University, January 1968.

2. C. P. Li, "Transport Coefficients of a Partially Ionized Plasma," Ph. D. thesis, Department of Aeronautics and Astronautics, Stanford University, June 1968.

3. S. Knöös, "Boundary Layer Structures in a Shock-Generated Plasma Flow. Part 1. Analysis for Equilibrium Ionization," J. Plasma Physics 2, 207-242, June 1968.

4. Collins, D. J., and Menard, W. A., "Measurement of the Thermal Conductivity of Noble Gases in the Temperature Range 1,500 to 5,000 Degree Kelvin," J. Heat Transfer, Trans. ASME, Series C, 88, 52 (1966).

5. Matula, R. A., "High Temperature Thermal Conductivity of Rare Gases and Gas Mixtures," ASME Paper No. 67-WA/HT-3 (1967).